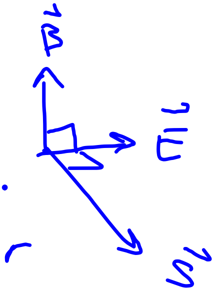
# Electromagnetic Waves.
Cont.

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \approx 3 \times 10^8 \, m/s$$

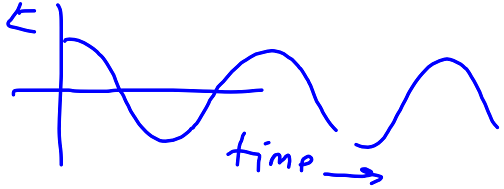
$$\vec{E} \perp \vec{B}$$



$$E = cB$$

Poynting Vector

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$



$$\frac{\text{Power}}{\text{Area}} = |\vec{S}| = \frac{EB}{\mu_0} = \frac{E^2}{c\mu_0} = \epsilon_0 c E^2$$

$$S_{av} = \frac{1}{2} \epsilon_0 c E_{max}^2$$

Intensity

energy density

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{1}{\mu_0}B^2$$

$$= \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\epsilon_0 E^2$$

$(E = cB$

$(c^2\epsilon_0 = \frac{1}{\mu_0}$

$$= \epsilon_0 E^2$$

momentum density

$$\frac{p}{V} = \frac{u}{c} = \frac{\epsilon_0 E^2}{c} = \frac{S}{c^2}$$

$$= \frac{I}{c^2}$$

$$\text{momentum density} = \frac{\text{Intensity}}{c^2}$$

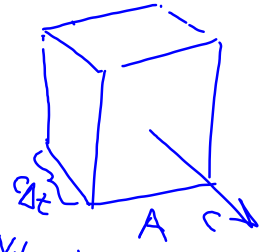
radiation pressure

= momentum/area/time

$$= \frac{(\text{momentum density})\,\text{Volume}}{\text{Area} \times \text{time}}$$

$$= \frac{\left(\frac{I}{c^2}\right) A c \Delta t}{A\,\Delta t}$$

$$= \frac{I}{c} = \text{radiation pressure}$$



Volume = $Ac\Delta t$

# Index of refraction

$$n = \frac{c}{v} = \frac{\text{speed of light in vac}}{\text{speed of light in materia}}$$

$> 1$ for any material

$= 1.0$ for vacuum

$n_{air} = 1.000293$

$n_{water} = 1.333$

$n_{glass} = 1.5$

$n_{diamond} = 2.4$

Q. How fast does light travel in diamond?

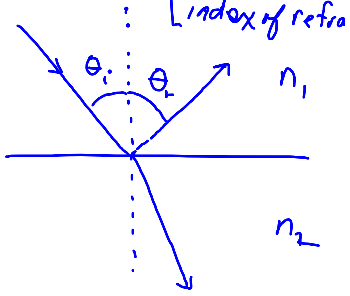
A. $n = \frac{c}{v} \Rightarrow v = \frac{c}{n} = \frac{3\times10^8 \, m/s}{2.4}$

$= 1.25 \times 10^8 \, m/s$

# Reflection & Refraction

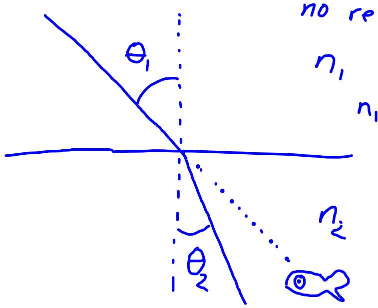
Interface = boundary between substances with different indices of refraction

[index of refraction $n = \frac{c}{v}$]



$\theta_i = \theta_r$

If $n_1 = n_2 \rightarrow$ no reflection & no refraction



$n_1 \sin\theta_1 = n_2 \sin\theta_2$

Snell's Law

Across interface frequency of waves is same

$v = \lambda f$ $\qquad n = \frac{c}{v}$ $\qquad v = \frac{c}{n}$

$$\lambda = \frac{v}{f} = \frac{c/n}{f} = \frac{c}{f}\frac{1}{n} = \frac{\lambda_0}{n}$$

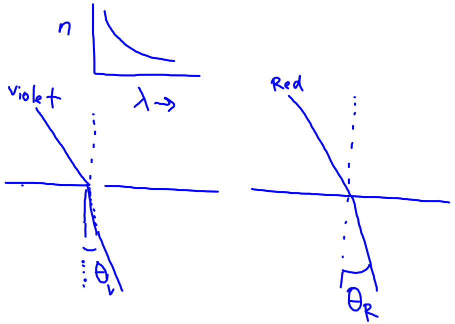
$$\boxed{\lambda = \frac{\lambda_0}{n}} \qquad \lambda_2 = \frac{\lambda_1}{n_2}$$

# Dispersion

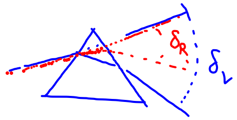
- the dependence of wave speed on wavelength. $v = v(\lambda)$

$$n = \frac{c}{v(\lambda)} \Rightarrow n = n(\lambda)$$

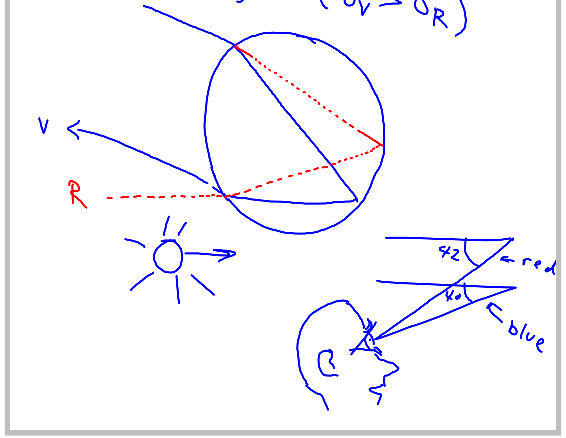
$n$ generally <u>decreases</u> with increasing $\lambda$



$$n_v > n_R \Rightarrow \theta_v < \theta_R$$



Violet light is refracted more than red light $(\delta_v > \delta_R)$



# Polarization

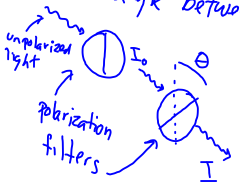
## ① Polarization by filter

$$I = I_0 \cos^2\theta$$

$I_0$ = intensity of polarized incident light (on filter)

$I$ = intensity of light leaving filter

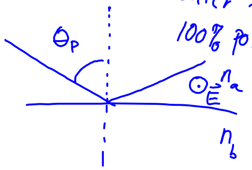
$\theta$ = angle between filters



$I = I_0 \cos^2\theta$ Malus' Law

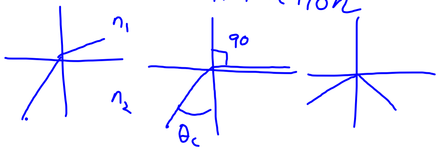
## ② polarization by reflection

(polarization angle) = angle of incidence at which there is 100% polarization



$$\tan\theta_p = \frac{n_b}{n_a}$$ Brewster's Law

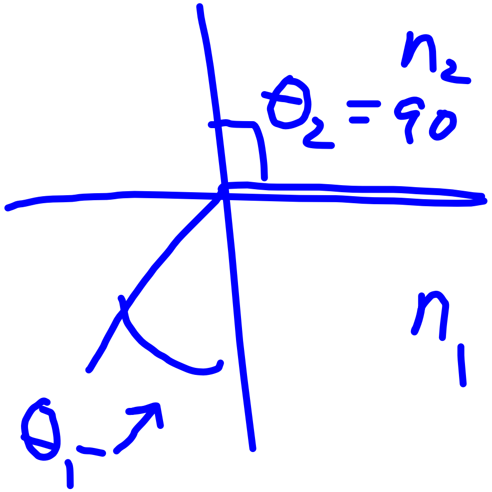
## Total Internal Reflection



$\theta_c$ = critical angle

= incident angle at which refracted angle $= 90^\circ$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

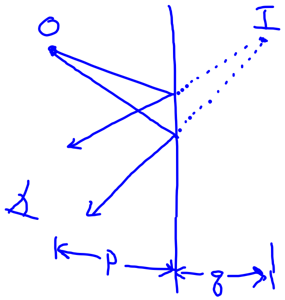


$n_1 > n_2$

$$\boxed{\sin\theta_1 = \frac{n_2}{n_1}}$$

$\theta_1 = \theta_c$

# Geometric Optics



p = distance of object from mirro

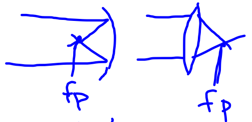
q = distance of image from mirror

Images can be "real" or "virtual"

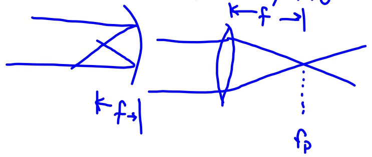
real image – actual point from which rays diverge. [Can see image on a screen placed at image position]

Virtual image – not a real image. Rays only appear to diverge from a point at image location

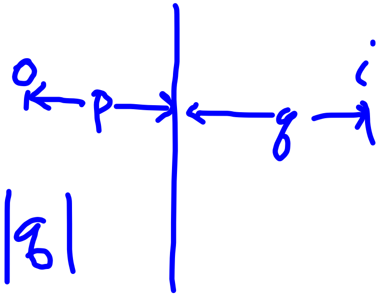
focal point – point at which parallel rays intersect



focal length = distance between reflecting or refracting surface & focal point



## Flat Mirror



$|p| = |q|$

- object distance = image distance
- No magnification
- focal length $= f = \infty$

## Concave Mirror

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$ ⇐ Mirror Equation

For $f = \infty$

$$\hookrightarrow \frac{1}{p} = -\frac{1}{q} \Rightarrow p = -q$$